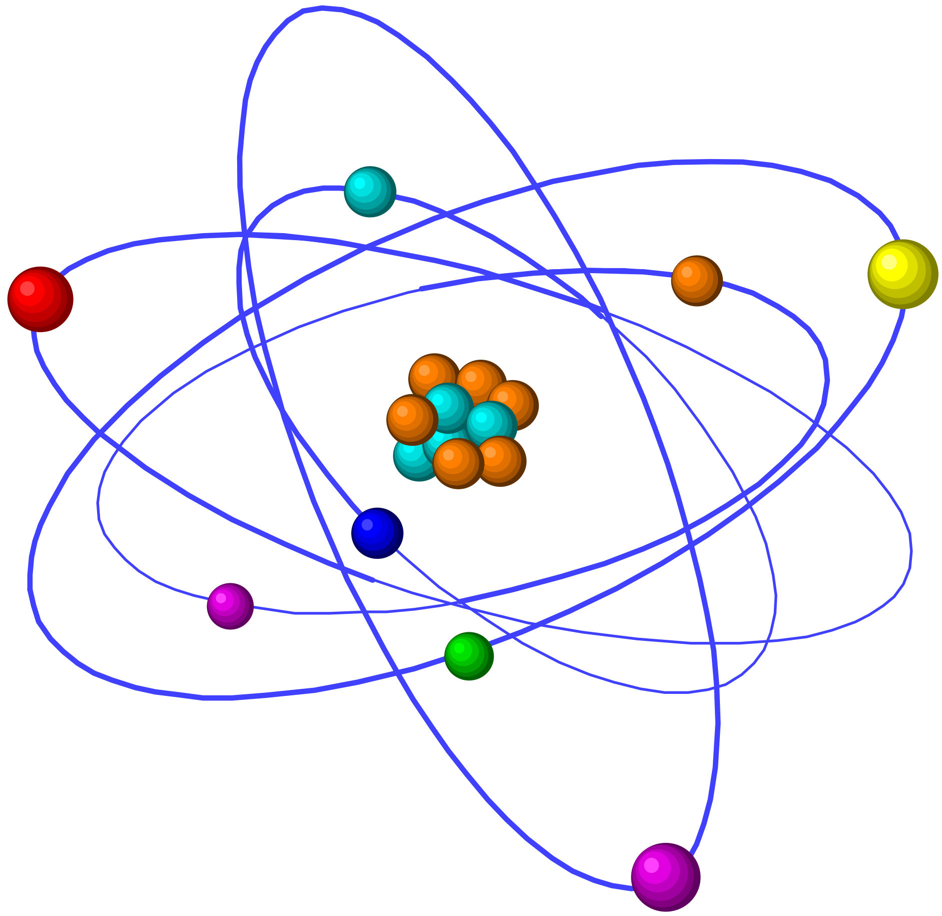
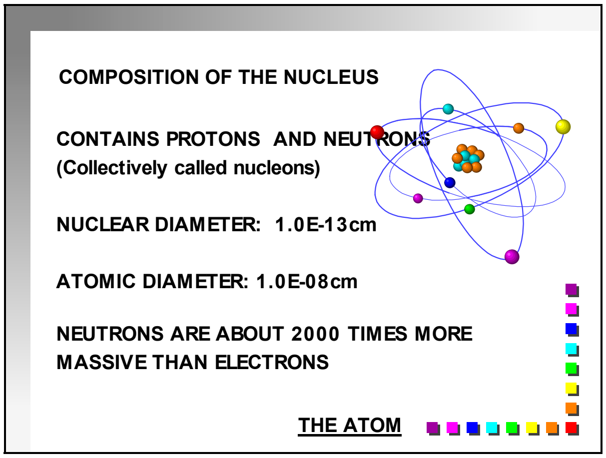


BASIC PRINCIPLES OF RADIATION

DEFINITIONS USED IN THIS SECTION:

Alpha particle (α)	An ionizing radiation particle composed of 2 neutrons and 2 protons with a +2 charge emitted from the nucleus of an atom.
Atom	Smallest particle of an element that possesses the chemical and physical characteristics of the element.
Atomic number (Z)	Number of protons in the nucleus of an atom, typically referred to as the Z number.
Beta particle (β)	Ionizing radiation particle emitted from the nucleus with a -1 charge and mass of an electron.
Decay constant (λ)	The probability that a fraction of the radioactive atoms present will decay in a given period of time. Numerically equal to the natural log of 2 divided by the half-life of the nuclide. Symbolized by the letter lambda (λ).
Electron	Particle with mass 1/2000 of the proton. Electrons have a –1 charge and orbit the nucleus of the atom. Electrons and beta particles are physically identical.
Excitation	The raising of an electron in an atom to a state of higher energy.
Gamma ray (γ)	Electromagnetic ionizing radiation emitted from the nucleus having no mass or charge.
Half-life ($T_{1/2}$)	The time required for one half of a large number of radioactive atoms to decay.
Ionization	Removal of an orbiting electron from an atom resulting in an ion pair consisting of a + charged atom and a — charged electron.
Isotope	An isotope is a specific type atom with discrete Z and mass number. All isotopes of an element have the same Z number and chemical characteristics but have different mass numbers.
LET	Linear Energy Transfer (LET) is a measure of the ionization that occurs per unit path length of travel of ionizing radiation.
Mass number (A)	The sum of the protons and neutrons in the nucleus of the atom.
Neutron	A particle with no charges that is part of the nucleus of atoms.
Nucleus	The part of the atom containing the protons and neutrons.
Proton	A positively + charged particle that is part of the nucleus of atoms.
Radiation, ionizing	Any electromagnetic (EM) or particulate radiation that will directly or indirectly result in ionization.

Radiation, non-ionizing	Electromagnetic (EM) waves with energy levels too low to ionize atoms. Non-ionizing radiation is composed of radio-frequency (RF) energy, including microwaves and radar and light energy from lasers.
Radioactive decay	The process whereby an unstable nuclide loses energy and becomes more stable.
Radioactive isotope	Isotope having an unstable nucleus that spontaneously decays by releasing energy in the form of particles or electromagnetic radiation.
Tritium	A radioactive isotope of hydrogen containing one proton and two neutrons. Tritium, often designated H-3, decays to helium by the emission of a beta particle with a maximum energy of 18.6 keV and an average energy of 5.7 keV. The radiological half-life is 12.28 years. Tritium is the most common radioisotope used in radioluminescent devices.
X-ray	Electromagnetic ionizing radiation, having no mass or charge, originating in the electron shells of atoms.



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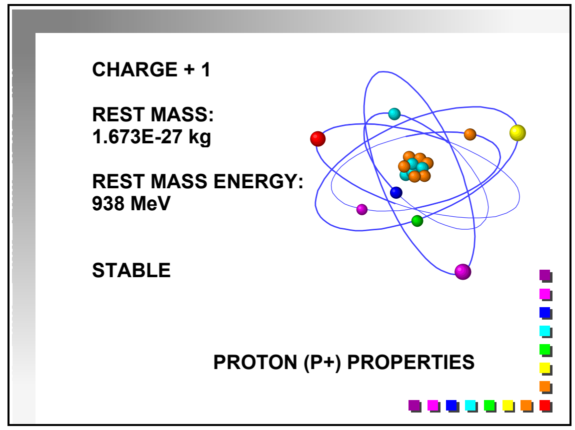

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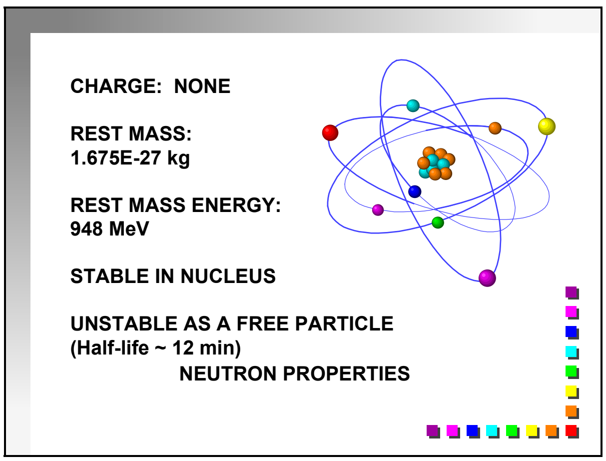

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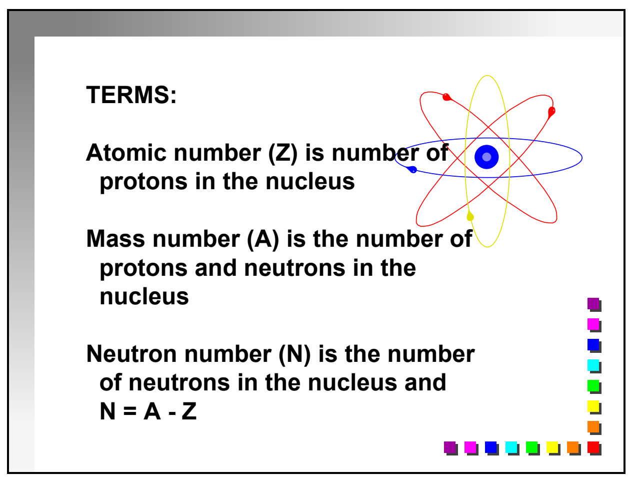

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SECTION 1. ATOMIC AND NUCLEAR STRUCTURE.

1-1. Introduction.

The world around us is composed of elements and combinations of elements, each with their own unique chemical properties. About 106 elements are known to man. Some examples are hydrogen, oxygen, carbon, gold, and silver. Substances such as water, wood, rock, rubber and coal, are combinations of these comparatively few elements. These combinations of elements are called compounds.

Each element can be denoted by a one or two letter chemical symbol; for example, H is the symbol for hydrogen, O is the symbol for oxygen, and Au is the symbol for gold. The periodic table of the elements, provided at the end of this section, lists the chemical symbol for each of the known elements. Compounds are denoted by combinations of element symbols and numbers that refer to the proportion of each element in the compound. Water, for example, which has two units of hydrogen for every unit of oxygen, is designated H_2O.

This section provides a review of the fundamental characteristics of radioactivity. The initial portion covers basic information about atomic structure and radioactive decay, then the properties of ionizing radiation are reviewed.

1-2. Atom Model.

The smallest unit of an element is the atom. An atom consists of a small, dense, positively charged nucleus surrounded by a cloud of negatively charged electrons.

(slide 1)

a. The Nucleus. The nucleus consists of two fundamental particles; protons and neutrons.

(slide 2)

(1) The proton is a positively charged particle with a unit charge. The mass of a proton is approximately 2000 times that of the electron. The number of protons in the nucleus is called the atomic number and is designated by the letter "Z". The atomic number is unique for each element; for example, if a nucleus contains six protons, the atom is a carbon atom; on the other hand, if a nucleus contains eight protons, the atom is an oxygen atom.

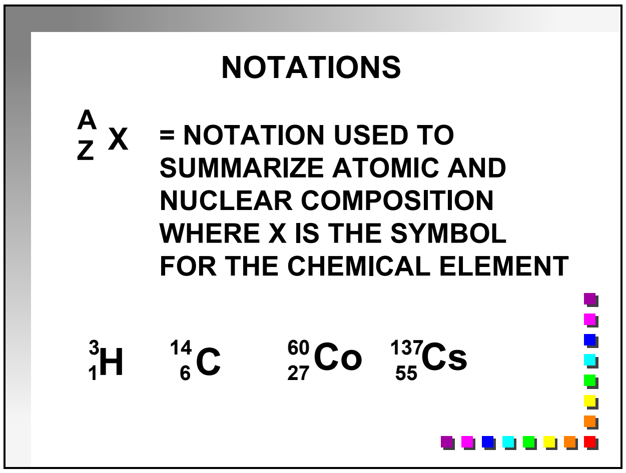
(Slide 3)

(2) The neutron is a particle that has no electrical charge and has a mass slightly greater than that of a proton. The nuclei of the atoms that make up a given element may contain varying numbers of neutrons. The number of neutrons in the nucleus, is designated by the letter "N". The number of neutrons influences the stability of the nucleus; that is, it determines whether the atom is radioactive.

(slide 4)

(3) The number of protons plus the number of neutrons in the nucleus is the mass number and is designated by the letter "A".

(4) The terms used are: Atomic Number (Z), the number of protons in the nucleus, the mass number (A), and the neutron number (N). $N = A - Z$.



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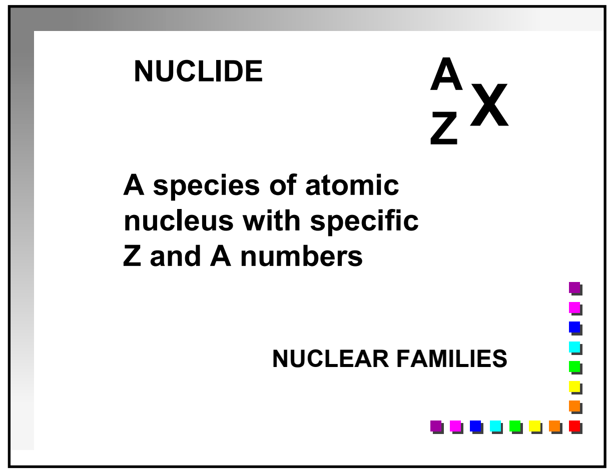

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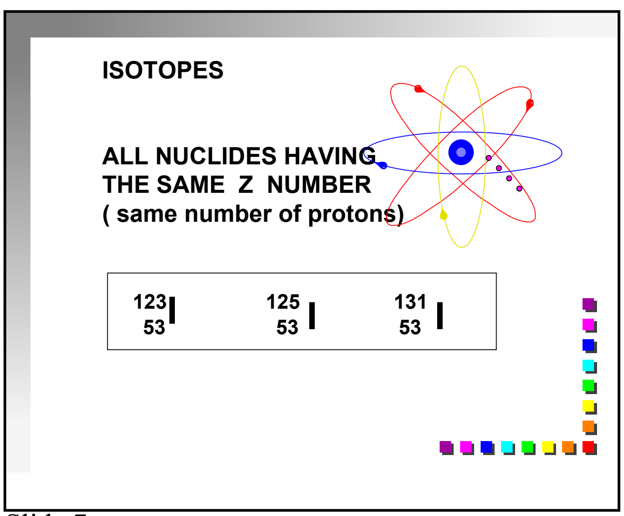

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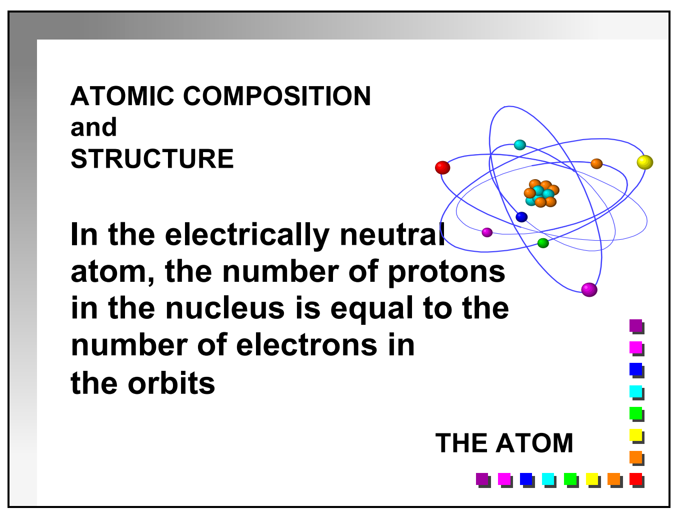

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(slide 5)

b. Isotopes. Isotopes are atoms of one element that have the same atomic number, or number of protons, but differ in neutron number. The isotopes of a given element have the same chemical properties and cannot be separated by chemical methods. However, the nuclear characteristics of the isotopes may be quite different; for example, some isotopes of an element may be radioactive while others are not. Hydrogen, the simplest element has three isotopes, these are ^{1}H, ^{2}H and ^{3}H. The third isotope, tritium, chemically behaves as hydrogen, but is radioactive. Isotopes of a given element are identified by their mass number, A, which is the total number of protons plus neutrons in the nucleus, that is, A = Z + N.

(slide 6)

c. Nuclides. Individual atoms are called nuclides; the radioactive forms are called radionuclides. An isotope or nuclide may be identified by its chemical symbol, X, with the atomic number, Z, as a pre-subscript and the mass number, A, as a pre-superscript.

<u>NUCLEAR NOTATION</u>

$$^{A}_{Z}X$$

A = Mass Number (slide 7)
X = Chemical Symbol
Z = Atomic Number

Because the atomic number, Z, is unique to a given element, it is often omitted from this notation. Sometimes a nuclide is designated by the full name of the element, or its chemical symbol, followed by a hyphen and the A number. Thus, ^{12}C, C-12, and carbon-12 are three ways of designating the same nuclide. In the past, the A number was written with the chemical symbols as a post-superscript, C^{12}.

The natural elements of the earth's crust or atmosphere are composed of a mixture of the isotopes of each element. The isotopes vary in percentage of natural abundance, that is, they do not all exist in equal amounts. For example, of all the oxygen atoms that occur on earth, 99.756% are ^{16}O, 0.034% are ^{17}O, and 0.205% are ^{18}O. The relative abundance of stable isotopes remains fairly constant over a wide geographic range.

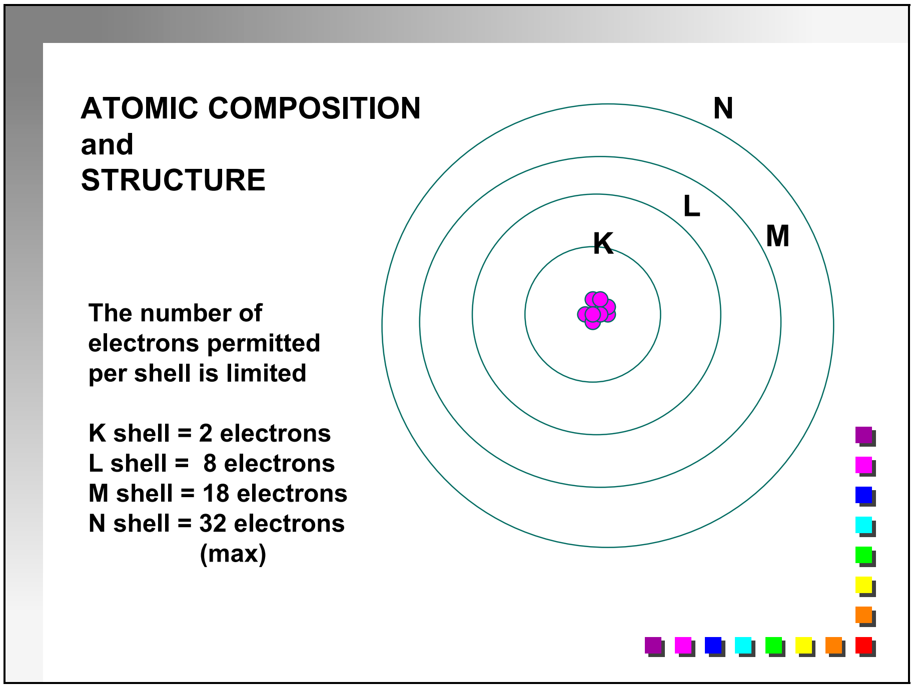
(slide 8)

d. Electrons. The nucleus is surrounded by electrons, which have a negative charge equal in magnitude, but opposite in sign, to that of the proton. In the neutral, uncharged atom, there is one electron outside the nucleus for every proton in the nucleus. The electrons can be thought of as occupying orbits, or shells, as shown. Because the protons give the nucleus a positive charge and the electrons have a negative charge, and because opposite charges tend to attract each other, there is an attractive force between an atom's nucleus and its electrons. The further the shell is away from the nucleus, the less the attractive force.

(slide 9)

The shells form a series of energy levels. The diameters of the shells are large in comparison with the diameter of the nucleus. The shells are normally identified by the letters (K, L, M, N, 0, P, or Q).

Because of the attractive force between the nucleus and the electrons, it takes a certain amount of energy to remove the electrons from the atom. The amount of energy required to completely remove


ATOMIC COMPOSITION
and
STRUCTURE
The number of
electrons permitted
per shell is limited
K shell = 2 electrons
L shell = 8 electrons
M shell = 18 electrons
N shell = 32 electrons
(max)
N
L
M
K
Slide 9

an electron from the atom is called the electron binding energy. This energy is different for each shell in the atom of any one element, and different for the same shell in different elements. The electrons nearest the nucleus, in the K shell, have a greater attraction to the nucleus than electrons farther from the nucleus. The electron binding energy associated with an inner shell is therefore greater than that of an outer shell. When one or more of the orbital electrons are removed, the atom is no longer in a neutral or stable state and is said to be ionized. The process of removing these electrons is called ionization.

The number of electrons permitted in shells K through N is limited to $2n^2$, where n is the number of the shell with K=1, L=2, etc. The K, or shell 1, contains a maximum of 2 electrons, the L, or shell 2, contains a maximum of 8 electrons, and the M shell contains a maximum of 18 electrons. Figure 1, below shows examples of electron structures.

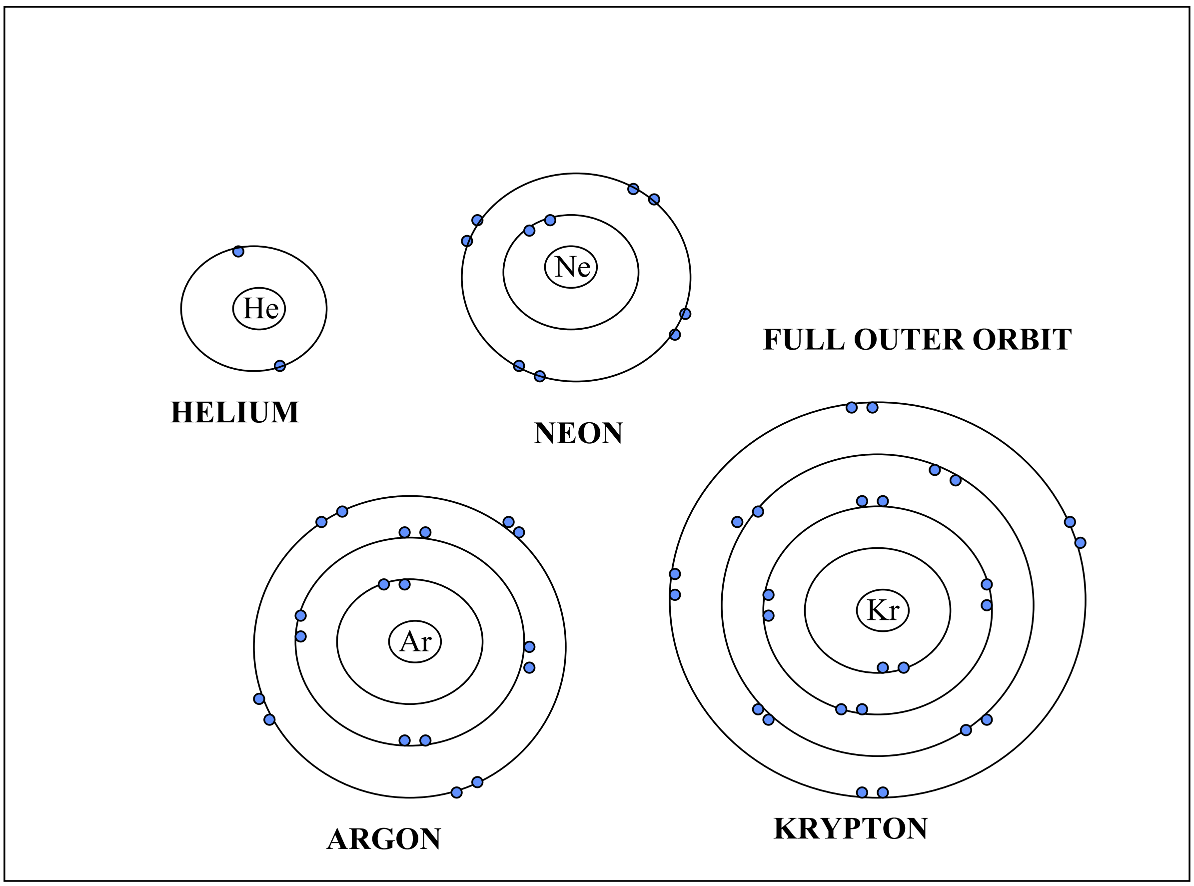
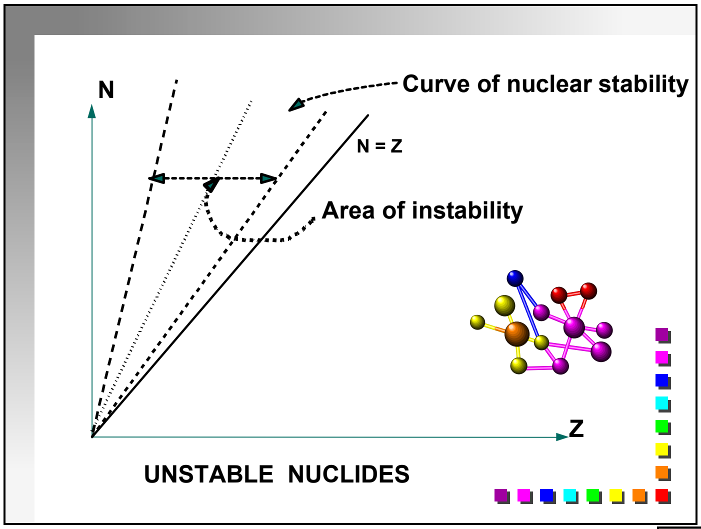


Figure 1. Electron Structure



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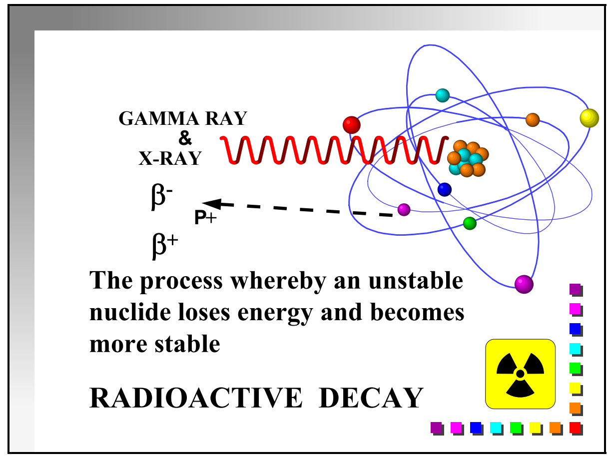

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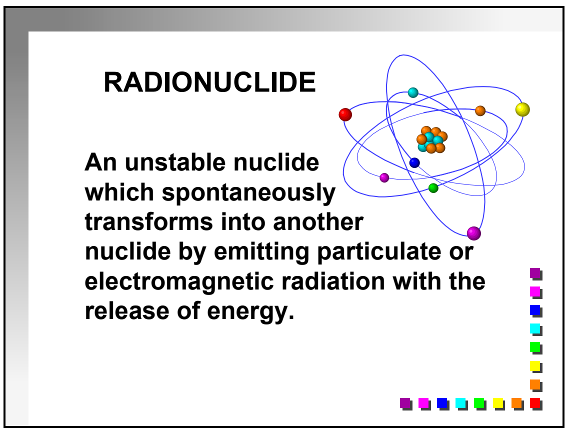

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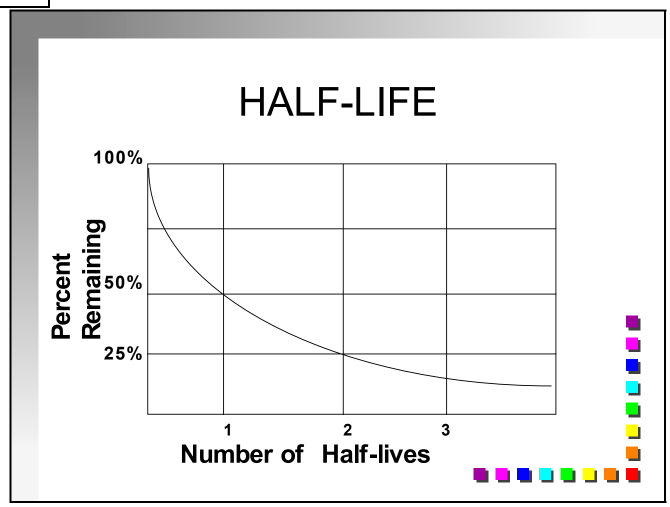

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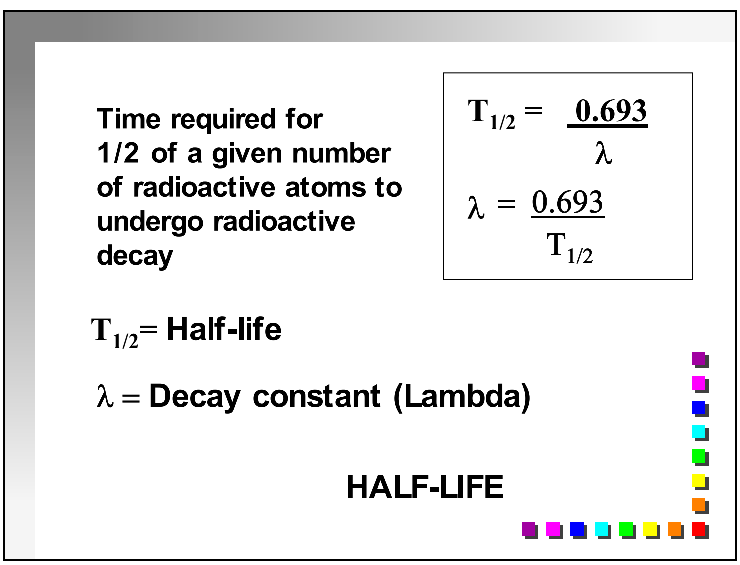

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SECTION 2. RADIOACTIVITY AND RADIOACTIVE DECAY.

2-1. Nuclear Stability.

Some atoms are unstable and undergo transitions that result in the release of particles and energy and the formation of a more stable atom. This process is called radioactive decay, and elements that undergo decay are called radioactive elements.

(slide 10)

If the N number of a nucleus is plotted as a function of the Z number of the nucleus, stable or unstable nuclei tend to be clustered about a line called the line of stability. In the case of nuclei of low Z, the most stable nuclei have approximately equal numbers of protons and neutrons. In the case of very heavy nuclei (those with many protons, or high Z), the nucleus is most stable if the number of neutrons in the nucleus is about 1.5 times the number of protons.

(slide 11)

Natural radioactivity is the result of the tendency of unstable nuclides to move to or toward the line of nuclear stability by undergoing radioactive decay. A nuclide undergoing radioactive decay is said to be a radionuclide.

(slide 12)

Radioactive decay is defined as a spontaneous, energy-releasing atomic transition that involves a change in the state of the nucleus of an atom. This change means that the atom changes from one nuclide (the parent) into a second nuclide (the daughter), or from one nuclear energy level to a lower energy level. Differences in the energy levels determine the amount of energy released by the transition. The transition must be spontaneous, that is, free from the influence of outside forces. It is possible to use machines such as cyclotrons, linear accelerators, or nuclear reactors to change the nucleus of an atom; however, such transitions are not considered radioactive decay.

2-2. Characterization of Radionuclides.

A radioactive nuclide, or radionuclide, can be characterized by its rate of decay, the energy released during the decay, and the type of radiation emitted by the decay.

(slide 13)

a. Rate of decay. All radionuclides do not decay at the same rate. Some decay very quickly, in a matter of a few seconds. Others may take days, weeks, or millions of years to decay. The rate of decay of a radionuclide is measured in terms of half-life.

(slide 14)

The half-life of a radionuclide, symbolized $T_{1/2}$, is the time required for a large number of radioactive atoms to decrease by one half. After one half-life, 50% of the original radioactive atoms remain; after two half-lives, 25% of the original radioactive atoms remain, etc. The half-life of a particular radionuclide may be found in the Table of Isotopes (Lederer and Shirley 1978) or Nuclides and Isotopes, Fourteenth Edition, (GE Nuclear Energy Operations).

Half-life is a statistical process. The concept of half-life does not apply to a small number of atoms. If you have two atoms of an element with a 2 day half-life you could not say that after two days you would only have one. The fact is, both may decay within a few minutes or may not decay at all. Radioactive decay is a random process.

The rate of radioactive decay may also be expressed in terms of the decay constant, lambda (λ), of the radionuclide. The decay constant indicates the probability that a fraction of radioactive atoms present will undergo radioactive decay in a given period of time. It is numerically equal to the

NUCLIDE	$T_{1/2}$	DECAY CONSTANT
^{3}H	12.3 yrs	5.63E-02 per year
^{32}P	14.3 days	4.84E-02 per day
^{226}Ra	1600 yrs	4.33E-04 per year

EXAMPLES OF HALF-LIVES AND DECAY CONSTANTS

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$$N_{(t)} = N_o e^{-\lambda t}$$

Where:

$N_{(t)}$ = Number of atoms at some time "t"

N_o = Number of atoms at time "0"

e = Base of natural logrithms

λ = The decay constant of the given nuclide

= $(\ln 2)/T_{1/2}$

t = time

Time units must be the same. ln 2 = 0.693

THE DECAY EQUATION

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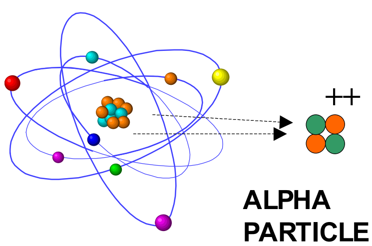

ALPHA PARTICLE

Charged Particle emitted from the nucleus with a mass and charge of two protons and two neutrons

Slide 17

$$2p + 2n = \alpha^{++}$$

$$^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha^{++}$$

Example:

$$^{210}_{84}Po \rightarrow {}^{206}_{82}Pb + {}^{4}_{2}\alpha^{++}$$

ALPHA DECAY

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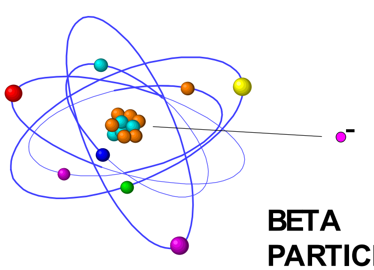

BETA PARTICLE

Charged Particle emitted from the nucleus with a mass and charge of the electron

Slide 19

$$p^{+} \rightarrow n + \beta^{+}$$

$$^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + \beta^{+}$$

Example:

$$^{62}_{29}Cu \longrightarrow {}^{62}_{28}Ni + \beta^{+}$$

BETA (+) DECAY

Slide 20

natural logarithm of 2, which is (0.693), divided by the half-life of the radionuclide. That is:

$$\lambda = (\ln 2)/T_{1/2} = 0.693/T_{1/2}$$

The half-life and decay constant are inversely related. A radionuclide with a long half-life has a small decay constant; a radionuclide with a short half-life has a relatively large decay constant.

(slide 16)

b. The decay equation. The decay constant is used in the following equation (the decay equation) when calculating the number of radioactive atoms present in a sample at any time.

$$N_{(t)} = N_o\, e^{-\lambda t}$$

where:	$N_{(t)}$	=	the number of radioactive atoms remaining after some time "t".
	No	=	initial number of radioactive atoms at time "0".
	e	=	the base of the natural logarithms ($2.71\overline{828}$).
	λ	=	the decay constant (of the given radionuclide).
		=	$(\ln 2)/T_{1/2} = 0.693/T_{1/2.}$
	t	=	the elapsed time.

Note: Time units must be the same. If half-life is in days the time, t, must also be in days.

(slide 17)

c. Types of radiation. Radioactive decay results in five of the six types of ionizing radiation: alpha particles, beta particles (positive and negative), gamma rays, x-rays, and neutrons. Protons, the sixth type of ionizing radiation are generated in accelerators. The two major modes of decay result in the emission of alpha particles or beta particles. Both of these decay modes may also be accompanied by the emission of gamma rays. The five types of ionizing radiation and the types of decay that produce them are described below.

(slides 18)

(1) **Alpha Particles**. Alpha particles are normally emitted from heavy nuclei that have an atomic number, Z, of 82 or more, except for some artificially produced nuclides. An alpha particle (α) is the helium atom nucleus. It has two protons, two neutrons and a net charge of +2. When a parent nucleus decays by alpha emission, the atomic number of the daughter nucleus is two less than that of the parent, and the mass number, A, of the daughter nucleus is four less than that of the parent. This reaction is summarized in Table 2.2.

(slides 19,20)

(2) **Beta Particles**. Beta particles result when a proton is converted to a neutron or a neutron is converted to a proton in the nucleus. These transitions enable an unstable nucleus to establish a more favorable neutron-proton ratio. After such a transition, two types of particles are ejected from the nucleus: a neutrino and a beta particle. A neutrino, symbolized by *v,* has no charge and essentially no mass and travels at the velocity of light. The neutrino does not easily interact with matter and presents no radiation hazard. A beta particle can have either a positive or negative charge, depending upon the type of transition occurring in the nucleus. If the beta particle has a negative charge, it is identical to an electron; if the beta particle has a positive charge, it is called a positron. When the nucleus has an excess number of neutrons, it undergoes a neutron-to-proton transition, and a negative beta particle, or electron, is ejected from the nucleus. As shown in Table 2.2, this negative beta decay results in the atomic number, Z, of the nucleus increasing by one. The mass number, A, remains constant.

(slide 21)

$n \rightarrow p^{+} + \beta^{-}$

$^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + \beta^{-}$

Example:

$^{32}_{15}P \rightarrow {}^{32}_{16}S + \beta^{-}$

BETA (-) DECAY

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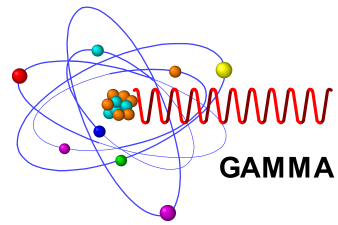

GAMMA RAY

Electromagnetic energy (radiation) of short wavelength emitted from the nucleus

Slide 22

$^{A}_{Z}X \rightarrow {}^{A}_{Z}X + \gamma$

Gamma ray emitted promptly after decay

$^{60}_{27}Co \xrightarrow{\beta^{-}} {}^{60}_{28}Ni + \gamma$

Gamma emission delayed, also called isomeric transition

$^{99m}_{43}Tc \rightarrow {}^{99}_{43}Tc + \gamma$

GAMMA EMISSION

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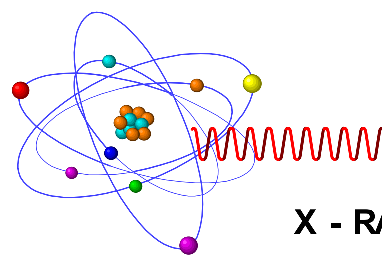


X - RAY

Electromagnetic energy (radiation) of short wavelength emitted from the electron orbits of the atom

Slide 24

Proton-to-neutron transition occurs when the nucleus has an excess number of protons. In this case, a positive beta particle, or positron, is ejected from the nucleus in what is called beta positive decay or positron decay. As a result of this decay, the atomic number, Z, decreases by one while the mass number, A, remains constant.

Sometimes a nucleus has an excess number of protons, and is unable to emit a positron. In this case, the nucleus captures an orbiting electron, which combines with a proton to form a neutron. This process is called electron capture decay, and the resulting nuclear change is identical to that of positron emission; the atomic number decreases by one and the mass number remains constant. Because an electron has been removed from its orbit, x-rays are produced as the electrons become rearranged (see Section (4), X-Rays).

Beta particles are emitted from the nucleus with spectrums of energies. The beta particle and the neutrino are emitted together and unequally share a given amount of energy. The beta particle may be ejected from the nucleus with essentially no energy, or with much energy. The average energy of the emitted beta particles is about one-third of the theoretical maximum energy for beta particles. Tables of beta energies indicate the maximum energy level for betas, but only a small fraction of beta particles possess the maximum energy level.

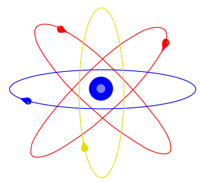
(slides 22, 23)

(3) **Gamma Rays**. When radioactive decay results in the emission of a particle from the nucleus, the nucleus is often left with an excess of energy, i.e., in an excited state. The excited nucleus then releases this excess energy in the form of gamma rays (photons, or wave packets of electromagnetic radiation) until the energy ground state of the nucleus has been reached. Sometimes the energy is emitted by one emission; at other times it is emitted in a series of emissions. The number and energy of gamma rays given off following a particle ejection is constant and a characteristic of the given radionuclide.

Gamma rays are usually emitted immediately after the particle is ejected, but sometimes the nucleus remains in a higher-energy state for a measurable period of time, up to several hours. The excited nucleus is then in an unstable, transient condition and is called an isomer of the ground-state nucleus. Isomers are nuclei that are identical to each other in all respects except for their energy state. The excited state is designated by writing a small "m", the symbol for "metastable", after the mass number of the nuclide; for example, ^{99m}Tc is an isomer of technetium-99 and decays to ^{99}Tc by emission of a gamma ray containing the excess energy.

(slides 24)

(4) **X-Rays**. If an electron is removed from an inner shell, a vacancy, or "hole", is formed in that shell. Due to the electrical attraction between the nucleus and the electrons, an electron from one of the outer shells may then be pulled into the vacancy. When this happens, the energy of the x-ray is equal to the difference between the electron binding energies of the two shells, which is then emitted from the atom in the form of electromagnetic radiation. This radiation is called characteristic x-ray radiation because the amount of energy released is characteristic of the given element. Characteristic radiation may be given off in the form of light, heat, or x rays, depending upon the energy difference. The capture of an orbital electron by a nucleus with excess protons (electron capture decay) results in a vacancy in the shell that the electron occupied. The shell most commonly affected is the K shell, being closest to the nucleus. Because an electron from an outer shell is pulled down to fill the vacancy in the K shell, electron capture is always accompanied by the emission of characteristic radiation in the form of x-rays. Like gamma rays, x-rays are photons, or packets of electromagnetic radiation. Although electromagnetic radiation exists as waves, when discussing the energy of electromagnetic radiation it is often convenient to think of the waves as existing in the form of wave packets, called quanta or photons.



NEUTRONS

Not normally emitted from common radionuclides.

Am - Be production:

$$ {}^{241}_{95}\mathrm{Am} \rightarrow {}^{4}_{2}\alpha \rightarrow {}^{9}_{4}\mathrm{Be} \rightarrow ({}^{13}_{6}\mathrm{C}^{*}) \rightarrow {}^{1}_{0}\mathrm{n} + {}^{12}_{6}\mathrm{C} $$

$$ \searrow {}^{237}_{93}\mathrm{Np} $$

$*$ Indicates excited state

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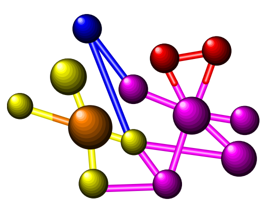

SOURCES OF FAST NEUTRONS

- NUCLEAR FISSION
- NUCLEAR REACTIONS

$$ \gamma + {}^{9}_{4}\mathrm{Be} \rightarrow {}^{8}_{4}\mathrm{Be} + {}^{1}_{0}\mathrm{n} $$

$$ \gamma + {}^{2}_{1}\mathrm{H} \rightarrow {}^{1}_{1}\mathrm{H} + {}^{1}_{0}\mathrm{n} $$

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(slide 25)

(5) **Neutrons**. Neutrons are not emitted from the more common radionuclides. Some of the heavier radionuclides emit neutrons by spontaneous fission, or splitting of the nucleus. The most common example of spontaneous fission is Californium-252 (^{252}Cf). Other sources of neutrons are listed below.

(slide 26)

(a) Some isotopes of boron, beryllium, lithium, sodium, fluorine, and other elements with a low atomic number emit neutrons when excited by alpha particles or gamma rays. These neutron sources are prepared by mixing a radioactive nuclide and a finely divided powder of the target substance. Examples of neutron sources are the mixed powders ^{241}Am:Be (americium and beryllium) and ^{21O}Po:Be (polonium and beryllium), and the chemical compound ^{239}PuF (plutonium fluoride). Neutron sources are kept in sealed metal containers, and the neutrons emitted have spectrums of energy.

The Am-Be neutron production is:

$^{241}Am + \alpha \rightarrow Be \rightarrow (^{13}C)^* \rightarrow n \rightarrow {}^{12}C$, ( )* indicates an excited state.

(b) When high-speed charged particles irradiate a suitable target material, the resulting nuclear reactions yield neutrons. These high-speed particles, or accelerator sources, can be used to produce neutrons of nearly the same energy.

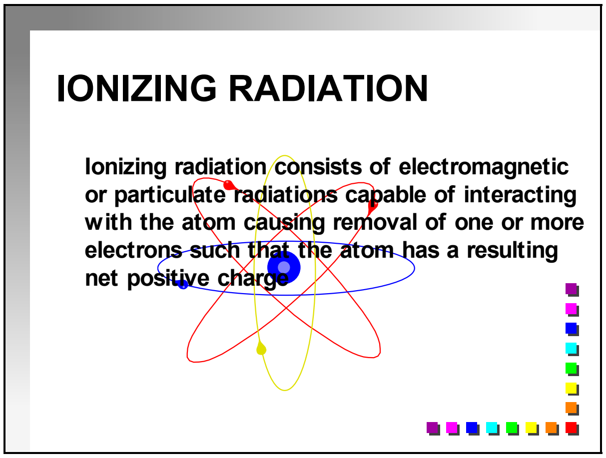
(c) The fission process in nuclear reactors produce large numbers of neutrons with spectrums of energies.

(6) **Characteristics of Radiation**. The five types of radiation can be distinguished by their physical characteristics, such as mass, electrical charge, and path length or range, as shown in Table 2.1.

Table 2.1. Radiation Characteristics

RADIATION			PATH LENGTH	
TYPE	MASS	CHARGE	AIR	SOLID
Alpha Particle	6.64E-24	+2	5 - 10 cm	24 - 40 um
Beta Particles	9.11E-27	+/– 1	0 - 18 m	0 - 1 cm
Gamma & X-Rays	------	0	0.1 - 100 m*	1 mm - 100 m*
Neutrons	1.67E-24	0	0 - 100 m	0 - 100 m

* There is no real endpoint for electromagnetic radiation: however, its intensity is reduced as it travels farther and passes through materials.



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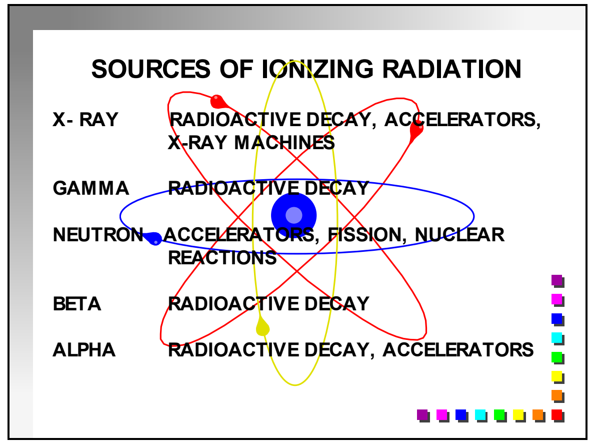

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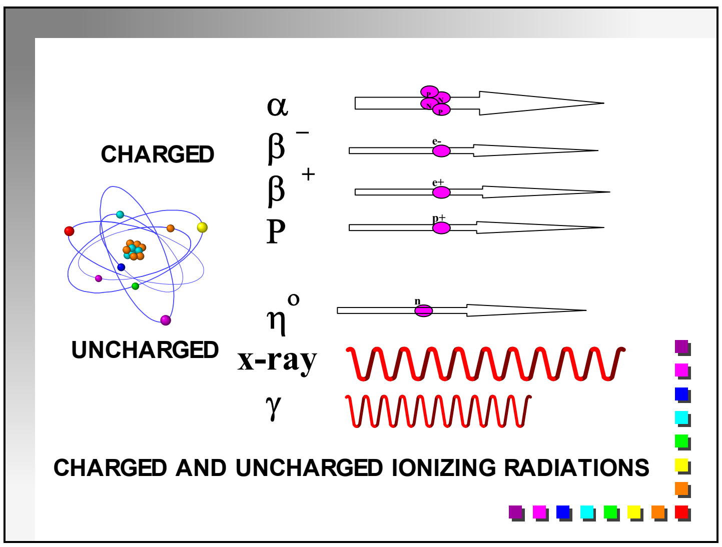

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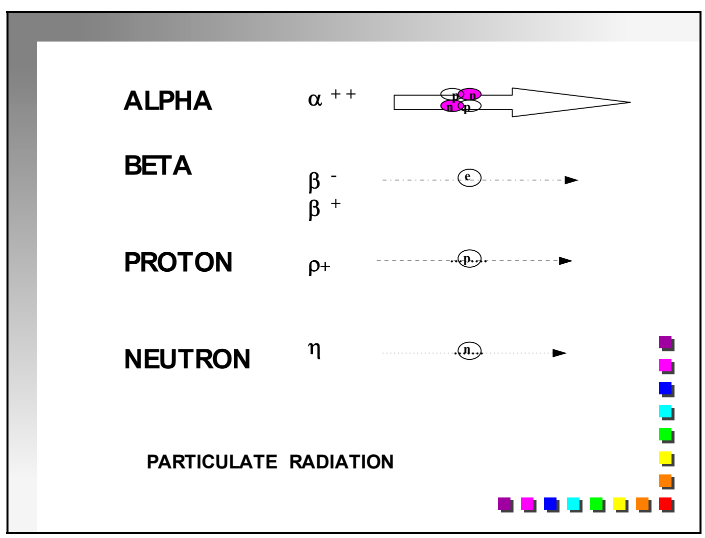

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Table 2.2 Effect Of Common Decay On the Parent Atom

	Change from Parent to Daughter Nucleus			
Decay Type	*Atomic Number (Z)*	*Neutron Number (N)*	*Mass Number (A)*	*Reaction Summary*
Alpha	-2	-2	-4	${}^{A}_{Z}X \rightarrow {}^{4}_{2}\alpha + {}^{A-4}_{Z-2}Y + hv$
Beta Negative	+1	-1	No Change	${}^{A}_{Z}X + \beta^{-} \rightarrow {}^{A}_{Z+1}Y + hv$
Beta Positive	-1	+1	No Change	${}^{A}_{Z}X + \beta^{+} \rightarrow {}^{A}_{Z-1}Y + hv$

d. The electromagnetic spectrum. (Figure 2.) This spectrum is divided into a number of regions, each representing wavelength intervals. All of these regions overlap, that is, the characteristics of the radiation change slowly with the change in frequency, and it is difficult to know exactly where one region ends and the next begins. Examples of electromagnetic radiation include radio waves and microwaves, infrared and visible light, and x and gamma radiation.

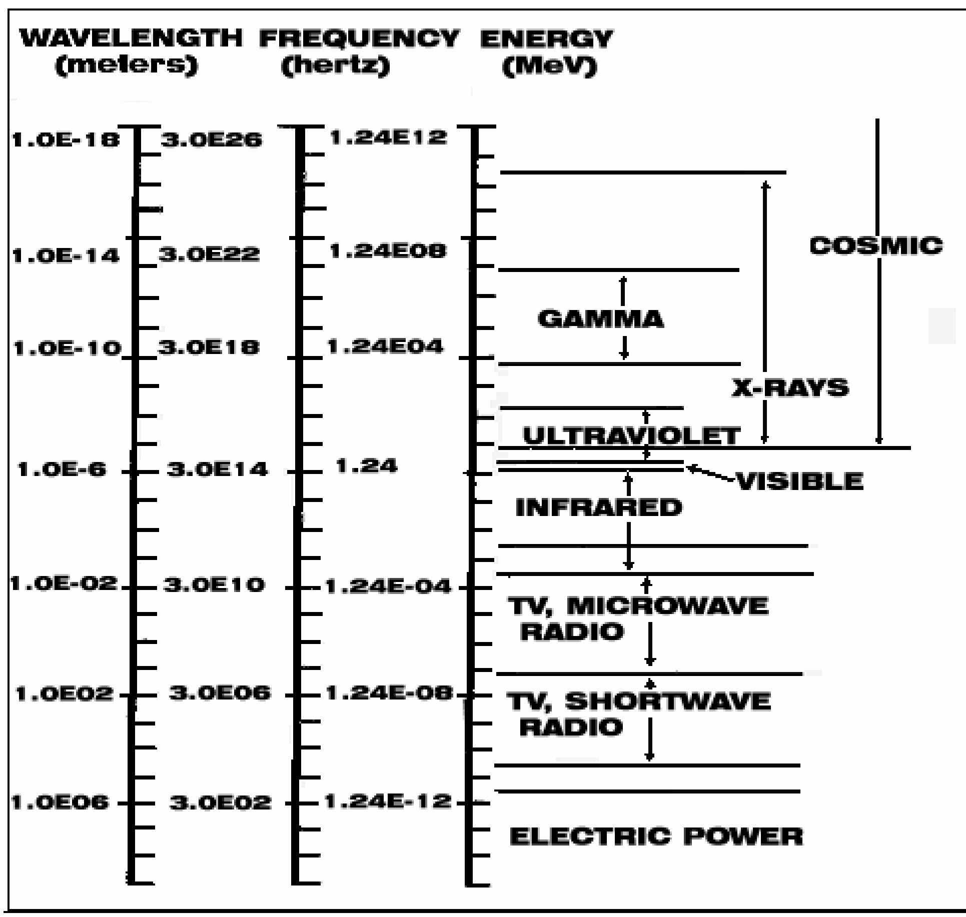
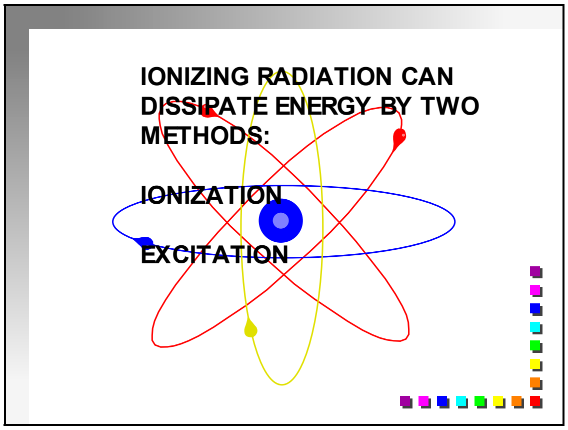


Figure 2. Electromagnetic Spectrum



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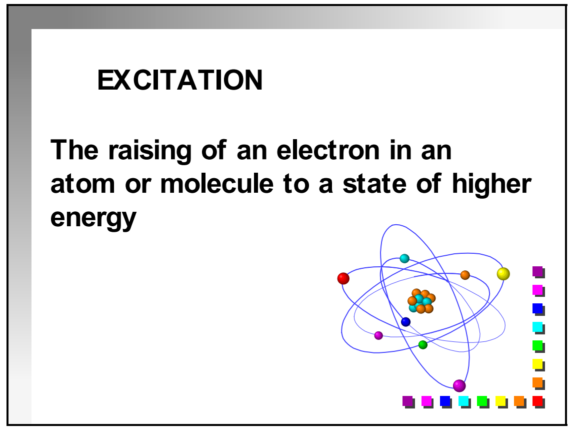

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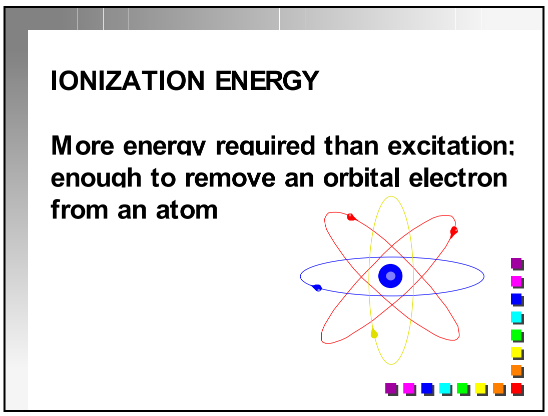

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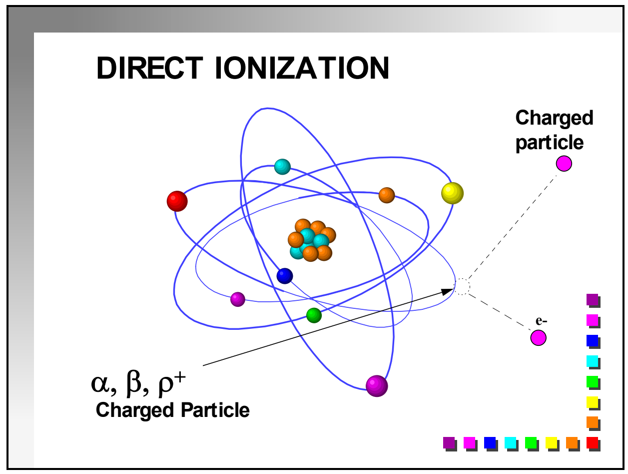

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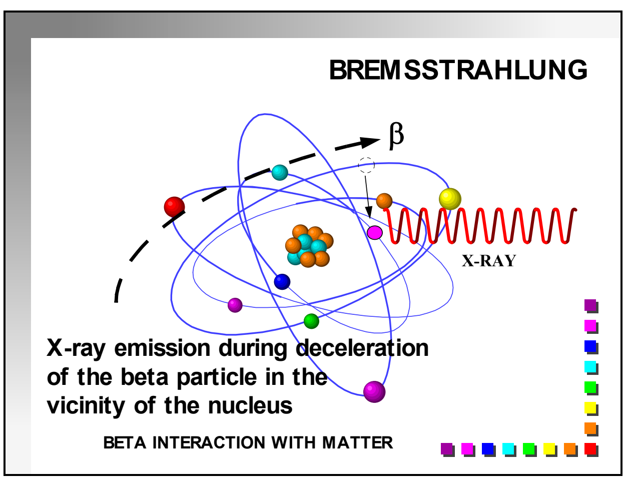

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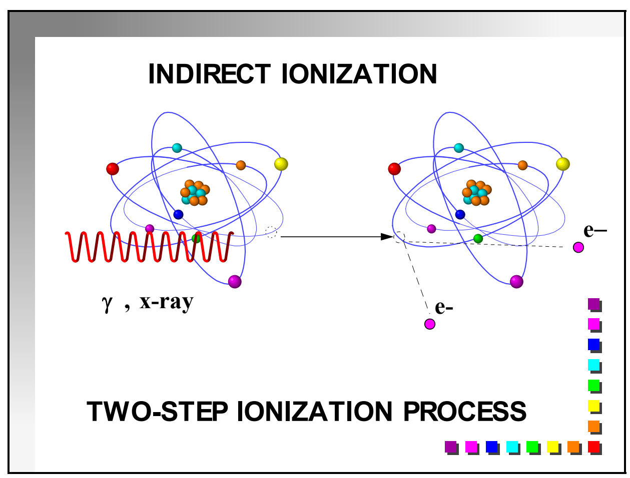

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SECTION 3. IONIZING RADIATION.

(slide 27)

Ionizing radiation consists of electromagnetic or particulate radiation capable of interacting with the atom and causing removal of one or more electrons such that the atom has a resulting net positive charge.

(slide 28)

3-1. Sources of Ionizing Radiation.

- X-ray: Radioactive decay, accelerators, x-ray machines.
- Gamma: Radioactive decay.
- Neutron: Accelerators, fission, nuclear reactions.
- Beta (-): Radioactive decay, accelerators.
- Beta (+): Radioactive decay.
- Alpha: Radioactive decay.

(slide 29)

a. Ionizing radiation can be categorized as follows:

- Uncharged, non-particulate (electromagnetic): X-rays and gamma rays.
- Uncharged, particulate: Neutrons
- Charged, particulate: Alpha, beta, and protons.

(slide 30)

b. Particulate radiations are:

- Alpha, beta, protons and neutrons.

(slides 31, 32, 33)

c. Ionization radiation dissipates energy by excitation or ionization.

- Excitation: The raising of an electron in an atom or molecule to a state of higher energy.

- Ionization: More energy required than excitation; enough to remove an orbital electron from the atom. Ionization may occur as a direct result of interaction or indirectly as a result of interaction.

(slide 34)

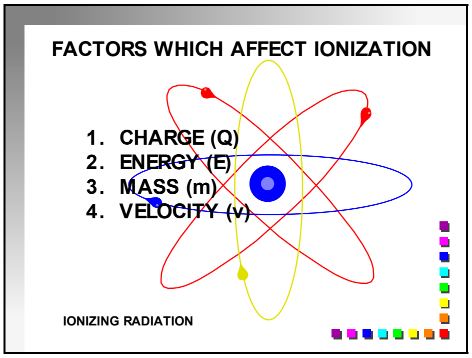
3-2. Directly Ionizing Radiations.

Directly ionizing radiations are charged particles that interact with the atom in a one-step process, to cause removal of one or more orbital electrons. Charged particles, such as alpha and beta radiations, are directly ionizing radiations.

(slide 35)

One important beta reaction is the process of Bremsstrahlung; a German term for "brake radiation." An x-ray is emitted when beta particles react with electrons in the absorbing medium. This is the reaction that produces x-ray radiation in the AN/UDM-2 RADIAC Calibrator Set, which has a beta source. The high energy beta emitted from the Strontium-Yttrium sources generates x-ray photons as it interacts with the shield material surrounding the source.

(slide 36)



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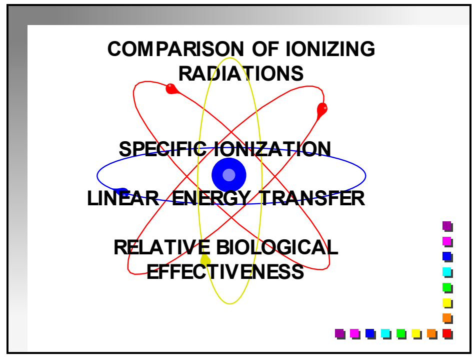

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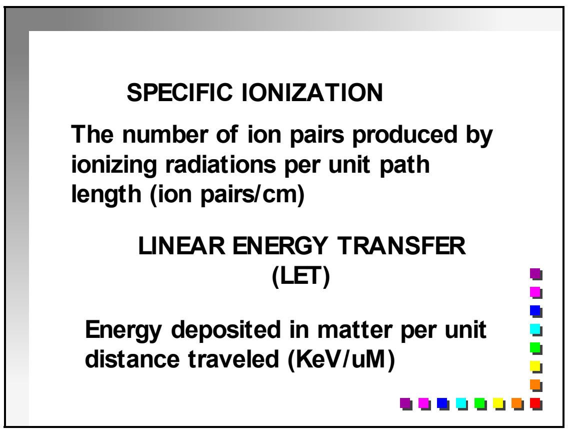

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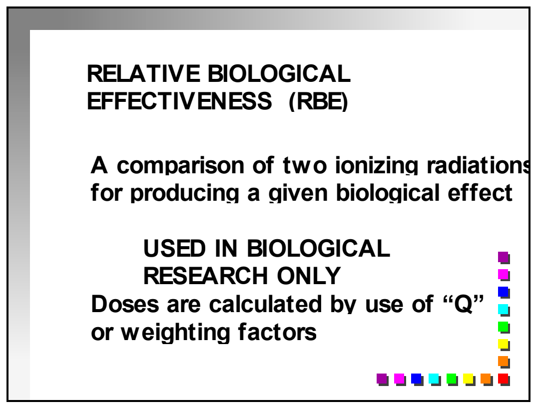

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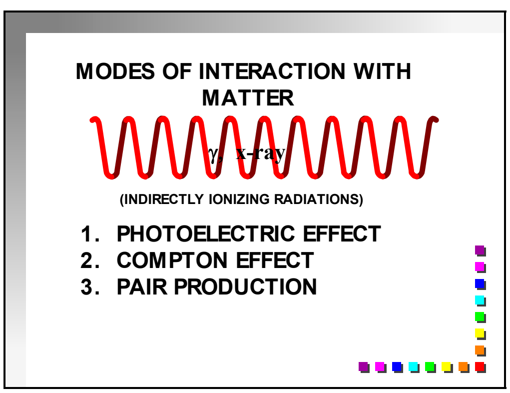

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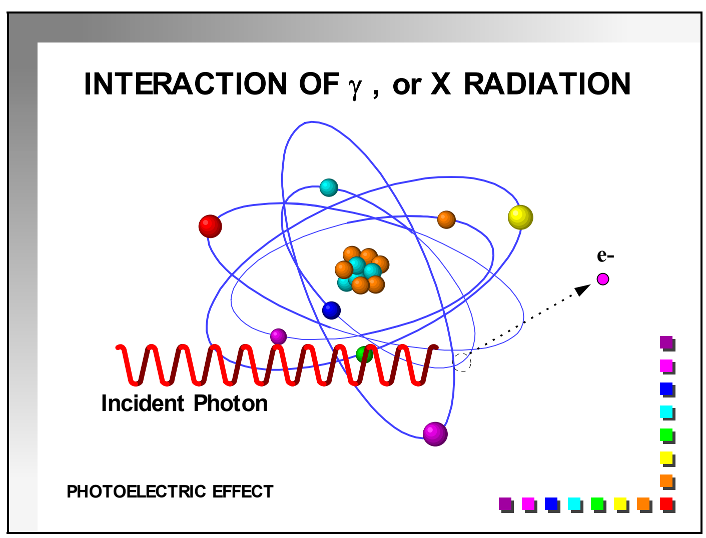

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3-3. Indirectly Ionizing Radiations.

Indirectly ionizing radiations cause ionization in a two-step process. Uncharged particles or waves such as, gamma, x-rays and neutrons are indirectly ionizing radiations. An example of indirect ionization is when a gamma ray interacts with an atom in the wall of the detector and an electron is ejected into the chamber where it causes direct ionization that can be measured.

3-4. Factors Affecting Ionization.

(slide 37)

- Charge. Alpha particles have more charge than beta particles and are more ionizing than beta particles.

- Energy. High energy particles are more ionizing than low energy particles.

- Mass. The more massive particles like the alpha particle are more ionizing than the radiations with no mass, like gamma and x-rays.

- Velocity. Fast particles are less ionizing than slow moving particles. Particles such as the neutrino, traveling at the speed of light, have very low ionizing capability.

3-5. Comparison of Ionizing Radiations. (slide 38)

(slide 39)

- Specific ionization. The number of ion pairs created per distance traveled (ip/cm).

- Linear Energy Transfer (LET). Amount of energy deposited per distance traveled. In general the higher the LET of the radiation, the shorter its range in matter and the greater the biological effect.

(slide 40)

- Relative Biological Effectiveness (RBE). A term used to compare the biological effect of two different types of radiation. This term is used by biologists. Radiation dose equivalent is calculated by use of the "Q" factor.

SECTION 4.0 RADIATION INTERACTIONS.

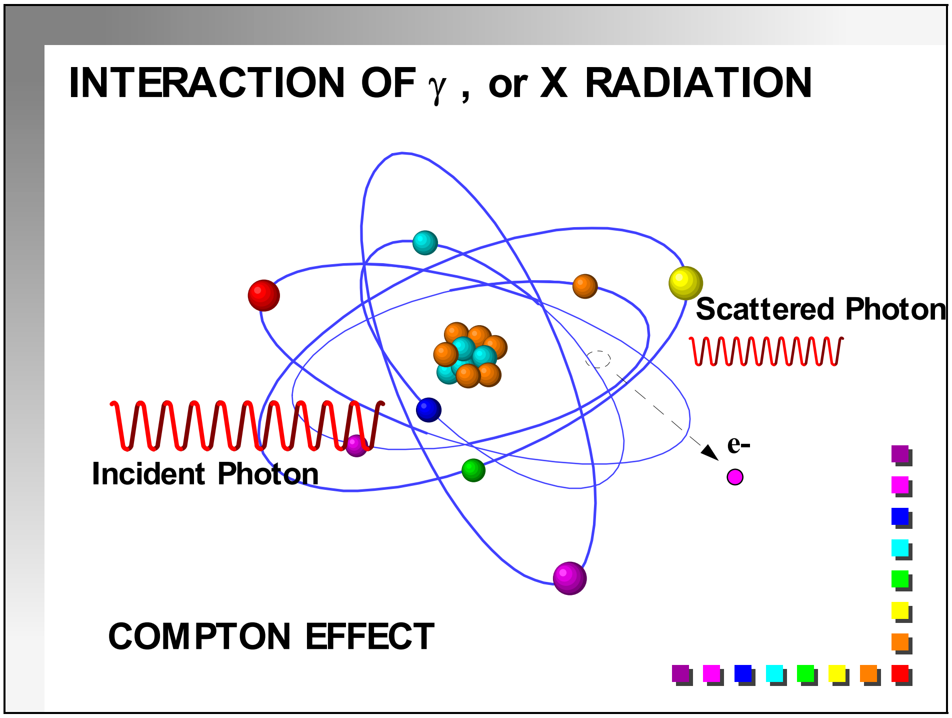
4-1. Interaction of Gamma Radiation with Matter. (slide 41)

As stated above, radiation interacts with matter by ionization or excitation. The interaction depends upon the type of radiation. Charged particles, alphas, and betas, react directly with the orbital electrons to cause ionization. Gamma radiations interact indirectly with both orbital electrons and the nucleus in one of the following three methods.

(slide 42)

a. *Photoelectric effect*. Occurs at low to medium gamma energies upon reacting with high Z materials, such as lead. The incident gamma is absorbed and an orbital electron is expelled. The orbital electron then expends energy as it is slowed down in the medium. The energy expended is in the visible light range when the medium is certain materials, such as a sodium-iodide crystal. (slide 43)

b. *Compton effect* (also known as compton scatter). Occurs with medium to high gamma energies. The incident gamma interacts with an electron, transferring some of its energy to the electron, which is



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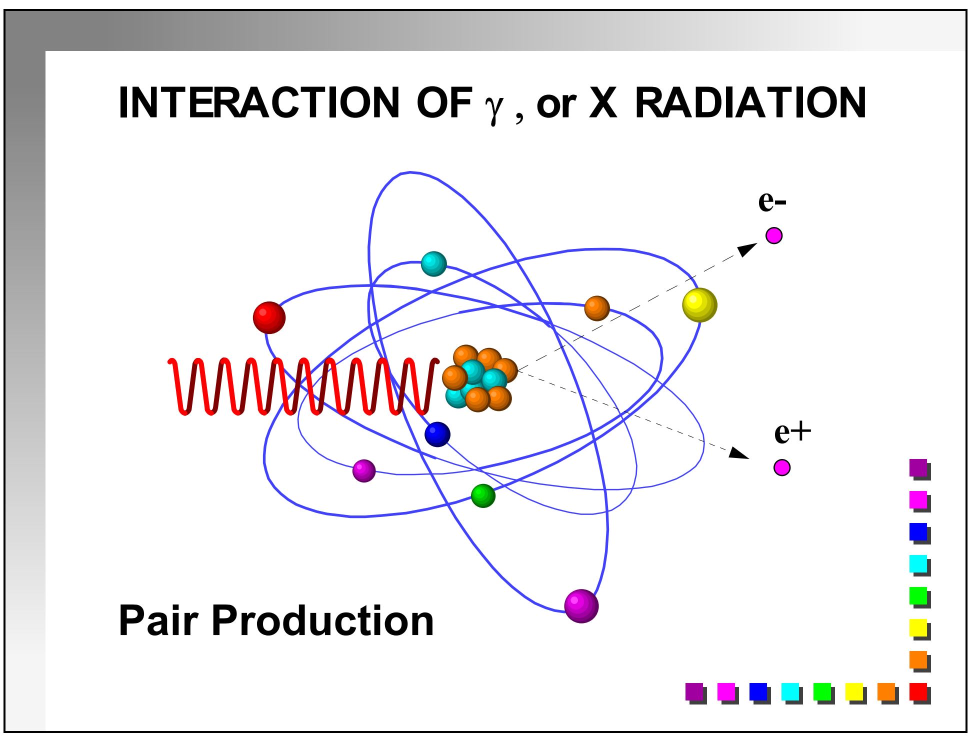

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emitted, and the gamma is scattered with less energy in another direction. This is the predominate reaction in biological materials with photon energies of 30 keV to 10 MeV.

(slide 44)

c. <u>*Pair production*</u>. Occurs at energies greater than 1.02 MeV. The incident gamma is absorbed, and two electrons (betas) are emitted, one with a negative charge and one with a positive charge. (These two particles will combine to yield two gamma photons of 0.51 MeV each. This is refered to as the annihilation reaction and the resultant gamma radiation is called annihilation radiation.)

4-2. Neutron Interactions with Matter.

Neutrons, like gamma rays are very penetrating. Because they have no charge they do not interact directly with electrons. Neutrons interact with the nucleus of the atom, however, they do interact with the nucleus in the manner that yields particles that can cause secondary ionization and excitation. Neutrons are not stable outside of the nucleus, they decay to form a proton and an electron.

4-3. Decay Pathways.

A radionuclide can undergo radioactive decay via more than one decay pathway. Each decay pathway consists of the emission of a particle followed, in most cases, by the emission of one or more gamma rays. Pathways differ in the manner in which the energy of decay is distributed between the particle emitted and the subsequent gamma rays. For example, radium-226 (^{226}Ra) can decay by five pathways, the most common pathway is the emission of an alpha particle with 4.78 MeV of kinetic energy. The resulting (daughter) nucleus, radon-222 (^{222}Rn), is not in an excited state, so no gamma is emitted. The next most common pathway is the emission of an alpha particle with a kinetic energy of 4.60 MeV. The ^{222}Rn daughter nucleus is in an excited state, and a gamma ray is emitted. For three additional pathways with alpha energies of 4.34, 4.19, and 4.16 MeV, the emission of gamma rays follows. A single nucleus can decay by only one of the various pathways, but because there are five potential pathways, it is sometimes said that ^{226}Ra has five alphas, or five potential alpha energies.

4-4. Decay Schemes.

Decay schemes are diagrammatic representations of radioactive decay pathways. These are used in many reference books to indicate the mode of decay, the decay scheme and the energy released during the decay event. Figure 2.1 shows the decay chain for Ra-226 to Rn-222.

In nature Uranium is made up of U-238, U-235 and U-234 with 99.3 percent of uranium being U-238.

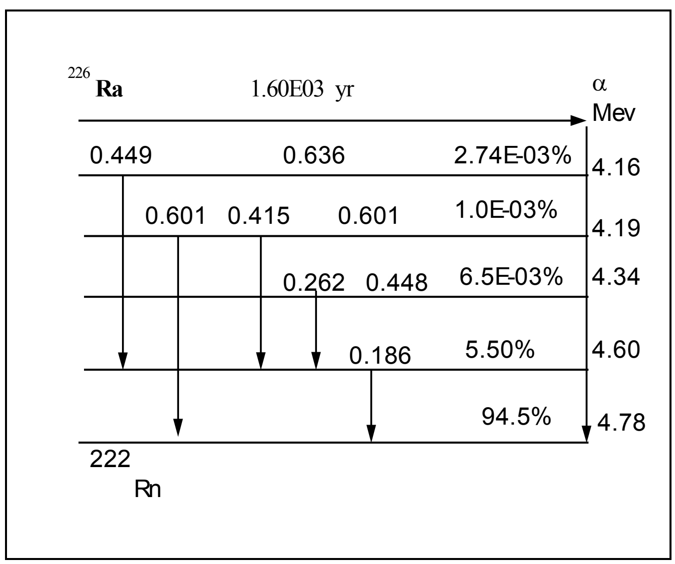

Figure 2.1. Radium Decay Scheme

Table 2.3 shows the decay chain for U-238.

Table 2.3 Uranium Decay Chain

Nuclide	Half-Life	Energy, MeV Alpha	Beta	Gamma
U-238	4.51E09 yr	4.18		
Th-234	24.1 days		0.193, 0.103	0.092, 0.063
Pa-234m	1.175 min		2.31	1.0, 0.76
Pa-234	6.66 hr		0.5	Many weak
U-234	2.48E05 yr	4.763		
Th-230	8.00E04 yr	4.685		0.068
Ra-226	1,622 yr	4.777		
Em-222(Rn)	3.825 days	5.486		0.51
Po-218(RaA)	3.05 min	5.998	unk	0.186
At-218(RaA')	2 sec	6.63	unk	
Em-218(RaA")	0.019 sec	7.127		
Pb-214(RaB)	26.8 min		0.65	0.352, 0.295 0.242
Bi-214(RaC)	19.7 min	5.505	1.65, 3.7	0.609, 1.12
Po-214(RaC')	1.64E-04 sec	7.680		
Tl-210(RaC")	1.32 min		1.96	2.36, 0.783 0.297
Pb-210(RaD)	19.4 yr	5.298	0.017	0.0467
Bi-210(RaE)	5.0 days		1.17	
Po-210(RaF)	138.4 days			0.802
Pb-210(RaG)	Stable			

From: Introduction to Health Physics, 1st Ed., Herman Cember, Pergamon Press, N.Y.

4-5. Determination Of Activity.

A radionuclide's activity at any time, $A_{(t)}$, is related to its decay constant, lambda, and the number of radioactive atoms present at that time, $N_{(t)}$, by the equation:

$$A_{(t)} = \lambda N_{(t)}$$

Remember that $\lambda = (\ln 2)/T_{1/2}$. From this equation, we learn that for a given sample activity, fewer radioactive atoms are present if the half-life is short than if the half-life is long.

The activity represents the disintegration rate of the sample; for every disintegration, one or more radiations may be emitted. As a result, two samples of equal activity may emit different amounts of radiation. For example, each disintegration of cobalt-60 (^{60}Co) involves the emission of one beta followed by two gammas, whereas each disintegration of ^{3}H and ^{14}C involve the emission of only one beta, without gammas. The activity of a radioactive sample is directly related to the number of radioactive atoms present. For this reason, the activity of the sample decreases exponentially as the number of radioactive atoms present decreases. That is, the activity of a sample of a radionuclide can be determined at any time using the following equation

$$A_{(t)} = A_o e^{-\lambda t}$$

where:

$A_{(t)}$	=	the activity present at some time, t.
A_o	=	the activity originally present.
e	=	the base of the natural logarithm (2.71828).
λ	=	the decay constant of the radionuclide = $\ln 2/ T_{1/2} = 0.693/T_{1/2}$.
t	=	the elapsed time.
$T_{1/2}$	=	the half-life.

APPENDIX A. **Practice Problems for Students.**

1. Given original activity = 23 microcuries on 25 Jan 1993
   Half-life is 1.5 years
   Find: Activity on 30 July 1995.

Ao = 23 uCi
Half life = 1.5 yr = 18 mo
Time: From 25 Jan 93 to 25 Jan 95 = 2 yr = 24 months. From 25 Jan 1995 to 30 July 95 is 6 months and 5 days. 5 days are 5/30 or 0.1666 mo. Total time is 24 months + 6.167 Months = 30.167 months.

DECAY EQUATION $A_{(t)} = A_o e^{-(\ln 2/\text{half-life})(\text{time})}$

$A_{(t)} = (23 \text{ uCi})\, e^{-(0.693/18)(30.17)}$

$A_{(t)} = 23 \text{ uCi } (e^{-1.1615})$

$A_{(t)} = 23 \text{ uCi } (0.313) = 7.19 \text{ uCi}$

2. Given: A_o = 30 millicuries, T1/2 = 12.3 yr, time = 4,500 days.

   Find activity now?

Time = 4,500 days/365 days per year = 12.32 yrs. As this is approximately 1 half-life. The activity now is approximately 15 millicuries. Use an intuitive approach, it will simplify the problem and you will know if you have a reasonable answer.

3. In July 1983 a tritium source had 10 curies. In July 1996 the activity will be? Half-life is 12.23 yr.

$A_{(t)} = 10 \text{ Ci } \times e^{-(0.693/12.23 \text{ yr})(13 \text{ yrs})} = 10 \text{ Ci } \times e^{-(0.7366)} = 10 \text{ Ci } \times 0.4787$

$= 4.787$ Ci